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Cancellation of MRI Motion Artifact in Image Plane

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Abstract* – In this study, a new algorithm for canceling a MRI artifact due to the translational motion in image plane is described. Unlike the conventional iterative phase retrieval algorithm, in which there is no guarantee for the convergence, a direct method for estimating the motion is presented. In previous approaches, the motions in the x(read out) direction and the y(phase encoding) direction were estimated simultaneously. However, the feature of x and y directional motions are different from each other. By anlyzing their features, each x and y directional motion is canceled by the different algorithms in two steps. First, it is noticed that the x directional motion corresponds to a shift of the x directional spectrum of the MRI signal, and the non-zero area of the spectrum just corresponds to the projected area of the density function on the x axis. So the motion is estimated by tracing the edges between non-zero area and zero area of the spectrum, and the x directional motion is canceled by shifting the spectrum in an reverse direction. Next, the y directional motion canceled by using a new constraint condition, with which the motion component and the true image component can be separated. This algorithm is shown to be effecttive by using a phantom image with simulated motion.

Keywords* – MRI, Motion artifact, Shifting, Fourier or Phase spectrum, Constraint condition, Artifact correction, Reconstructed

I. INTRODUCTION

Magnetic resonance imaging(MRI) is widely used a major diagnostic modality because of its many promising and substantial capabilitics for investigating body organs like espically the brain, spine. In two-dimensional Fourier transform MRI, it takes several minutes to obtain an image with a standard spin echo sequence. Body motions of injured patients including children are unavoidable during conventional magnetic resonance data acqusition. As a consequence, the motions cause ghostlike artifacts in the reconstructed image. The goal of this study is to cancel the MRI artifact due to the 2-D translational motions in image plane. A new approach using post-processing algorithm is proposed in this work.

For the purpose of correcting the motion artifact, various approaches to correct the motion artifact have been proposed. Some of them use special pulse sequences for suppressing the motion artifact[1 ~ 5]. However, such an approach is not taken here because that the adjustment of the hardware is difficult. Some other approaches only using post-processing are also proposed for this purpose. In the case of them, a prior knowledge of motion such as periodic motion is required[6 ~ 8]. Hedley et al. proposed an artifact cancellation method for 2-D translational rigid motions in an image plane[9 ~ 11]. The features of the method are as follows; First, no prior knowledge of the motion is required, Second, the motion may be either periodic or random, Third, no modification is made to a standard pulse sequence.

The region of the image is assumed to be known and to be used as a boundary condition. The phase of data is corrected using an iterative phase retrieval algorithm. The algorithm may take a lot of time because it uses an iterative process, and even has no guarantee for the convergence[12 ~ 14].

This method has the same restrictions of motion and the same features of the method as the Hedley's method. But the problem of convergence is avoided by not using any iterative procedure. On the basis of this MRI principle, the property of the influence of the motion in each of the x(signal readout) direction, and y(phase encoding) direction is analyzed, respectively. In order to correct the artifact due to the x directional motion, the x directional Fourier spectrum of the MRI signal is analyzed and utilized. It can be regarded as a Fourier weighted projection of the density function onto an x axis. Hence, the motion in x direction corresponds to the shift of the spectrum's edge without regard to the motion in the y direction. On the basis of this important property, the motion in the x direction is estimated, and the artifact of the motion can be canceled by shifting the spectrum in the reverse direction. On the other hand, in this phase of the x directional spectrum, the relation between the motion component and the true image component is just an algebraic sum. On the basis of the feature of the density function and the property of the Fourier transform, a new constraint for the true image component is proposed in this study. The y directional motion component can be extracted from the phase of the Fourier spectrum by using this constraint condition. The effectiveness of the algorithm is shown by simulations using a phantom with 2-D translational motions.

II. THE MRI SIGNAL AND MOTION ARTIFACT

MR imaging takes N time intervals.The MRI signal obtained in the n-th time interval is expressed as follows:

$$f_n(t) = \frac{1}{N}\sum_x \sum_y \rho(x, y) e^{j\gamma(G_x tx + G_y \tau n y)} \qquad (1)$$

Where, $\rho(x, y)$ is the density distribution of the target, G_x and G_y are the gradients of the magnetic field in the x and y directions, respectively, and γ and τ are constants. Therefore, the MRI signal can be regarded as a 2-D inverse Fourier transformation of the density distribution $\rho(x, y)$. Meanwhile, the MR image can be calculated by the 2-D Fourier transformation of the MRI signal.

In the procedure of taking a MR image, the period of intraview is just about dozens of milliseconds, but the period of interview is about one second and much longer than the period of intraview, Hence,the interview motion is the main factor of the patient's motion, and the intraview motion is neglected. When the motion is translational motion in an image plane, the corrupted MRI signal $f'_n(t)$ is given by

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$$f_n^{'}(t) = \frac{1}{N}\sum_x\sum_y \rho(x, y)e^{j\gamma G_x(x+\Delta_x(n))t + G_y(y+\Delta_y(n))n\tau} \tag{2}$$

Where, $\Delta_x(n)$ and $\Delta_y(n)$ is the translational motion in the x and y directions, respectively. Translational motion causes phase shift in the MRI signal, so some artifact will occur in the reconstructed image by the 2-D FFT of the $f'_n(t)$ as shown in Fig. 1.

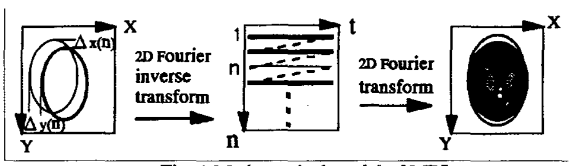

Fig. 1 Mathematical model of MRI

III. CANCELLATION OF THE ARTIFACT DUE TO 2-D TRANSLATIONAL MOTION

As the major motion is assumed to be the interview motion here, each MRI signal in one x directional line has the same motion. And the x directional Fourier spectrum F_{xn} of MRI signal can be calculated without data corruption. Further, the F_{xn} is analyzed here, instead of the general 2-D FFT of the corrupted MRI signal. When motion does not exist, F_{xn} is given by

$$\begin{aligned} F_{xn} &= \tau_t[f_n(t)] = \frac{1}{\sqrt{N}}\sum_t f_n(t)e^{-jk_x tx} \\ &= \frac{1}{\sqrt{N}}\sum_y \rho(x, y)e^{jk_y n\tau y} \end{aligned} \tag{3}$$

However, if motion exists, the x directional Fourier spectrum of the corrupted signal $f'_n(t)$ will be given by

$$\begin{aligned} F'_{xn} &= \tau_t[f'_n(t)] = \frac{1}{\sqrt{N}}\sum_t f'_n(t)e^{-jk_x tx} \\ &= \frac{1}{\sqrt{N}}\sum_y \rho(x-\Delta_x(n), y)e^{jk_y(y+\Delta_y(n))n\tau} \\ &= F(x-\Delta(n), n)e^{jk_y\Delta_y(n)n\tau} \end{aligned} \tag{4}$$

With regard to the F'_{xn}, the effect due to the x directional motion $\Delta_x(n)$ results in a position shift, and the effect due to the y directional motion $\Delta_y(n)$ results in a phase shift. The motion in different direction takes different form. By analyzing the F'_{xn}, the motion in each direction is extracted in different ways. If the motion components are known, the F'_{xn} can be corrected and the motion artifact is canceled in the MRI.

A. X DIRECTIONAL CANCELLATION ALGORITHM

One-shot x directional motion causes a shift of F_{xn} in the corresponding line. On the other hand, the x directional Fourier spectrum can be regarded as the projection of the density distribution onto the x axis. Therefore, the non-zero area of the amplitude of the F'_{xn} just corresponds to the projected position of the target at the n-th view. When motion does not occur, the edges between zero and non-zero of the amplitude of the F_{xn} will take two strait lines along the y direction. When the target moves $\Delta_x(n)$ at the n-th view, the F'_{xn} will shift a $\Delta_x(n)$ in the same direction, which is shown in fig. 2. Further, the motion in the y direction only affects the phase of F'_{xn}, and it does not affect the amplitude as shown in Eq. (4). Therefore, the x directional motion corresponds to the shift of the spectrum' s edge without regard to the y directional motion. On the basis of this important property, the x directional motion can be estimated by tracing the edge of the amplitude of the spectrum using a conventional algorithm no matter whether the y directional motion occurs or not. Therefore, the motion artifact in x direction can be canceled by shifting the Fourier spectrum in the opposite direction.

B. Y DIRECTIONAL CANCELLATION ALGORITHM

On the basis of the features of the Fourier transform, a new constraint for the separation of the y directional motion is proposed in this section. After canceling the x directional motion component, the remaining motion component is only the y directional motion component. The Fourier spectrum F'_{xn} has become into F''_{xn} which is given by

$$\begin{aligned} F''_{xn} &= e^{jk_y\Delta_x(n)n}F_{xn} = e^{jk_y\Delta_x(n)n} \bullet Ae^{j\phi_{xn}} \\ &= Ae^{j\phi'_{xn}} \end{aligned} \tag{5}$$

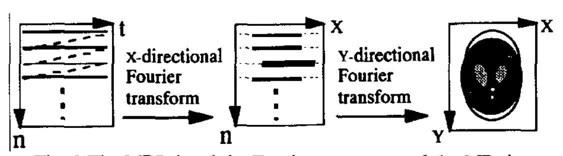

Fig. 2 The MRI signal, its Fourier spectrum and the MR image

where, A and ϕ_{xn} is the amplitude and the phase of F_{xn}, respectively. The ϕ_{xn} is the component of the true image, and it is called the phase of image here. ϕ'_{xn} is the phase of F''_{xn}, and it is called the phase of MRI here. The y directional motion component only occurs in the phase of the F''_{xn}. In the case of reconstructed image, one shot motion causes a complicated artifact. However, in the phase of F''_{xn}, the relation between the motion component and the true image component is just an algebraic sum as follows:

$$\phi'_{xn} = nk_y\Delta_n + \phi_{xn} \tag{6}$$

On the other hand, the phase of MRI ϕ'_{xn} can be calculated as follows:

$$\phi'_{xn} = \tan^{-1}\frac{\mathrm{Im}[F'(x,n)]}{\mathrm{Re}[F'(x,n)]} + m_n\pi \tag{7}$$

where, m_n is an integer. Hence, the left side of Eq. (6) is known. The problem is how to separate the motion component and the phase of image ϕ_{xn}.

To solve this problem, it is noticed that the F_{xn} is the x directional Fourier inverse transformation of the density function. According to the features of density function, a new constraint of the true image component F_{xn} is proposed as follows:

If the density function along a y directional line is symmetric, then the phase of image ϕ_{xn} on the line is a linear function of n, corresponding to y position.

Hence, the departure part from the linear function is just the motion component. The artifact due to the y directional motion can be suppressed finally by using this constraint condition.

C. EXPLANATION OF THE CONSTRAINTS

Generally, the y directional density distribution is random, however, the density of a y directional slice line which passes through the subcutaneous fat area is nearly symmetric. As shown in Fig. 3(a), if density distribution is symmetric to the origin, it is a real even function. On the basis of the features of Fourier transformation, the imaginary of its Fourier transformation is zero, that is, the phase of the spectrum is zero. Furthermore, as shown in Fig. 3(b), if the density distribution $\rho'(x,y)$ is symmetric about the axis $y = y_c$, according to the Fourier transform shift theorem, the following relation is satisfied:

$$\tau_y[\rho'(x,y)] = e^{jnk_y y_c} \bullet \tau_y[\rho(x,y)] \tag{8}$$

Hence, if the density function along a y directional line is symmetric, then the phase of the image ϕ_{xn} on the line is a linear function of n, and that is,

$$\phi_{xn} = nk_y y_c \tag{9}$$

This relation is used as a constraint for the phase of the image. By substituting Eq. (9) in Eq. (6), the following relation is obtained.

$$\frac{\phi'_{xn}}{nk_y} = y_c + \Delta_n \tag{10}$$

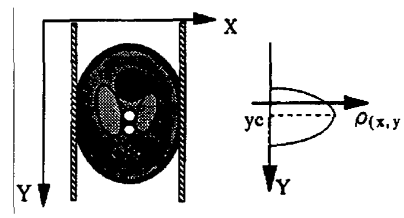

Fig. 3(a) Symmetric density distribution on a y directional line

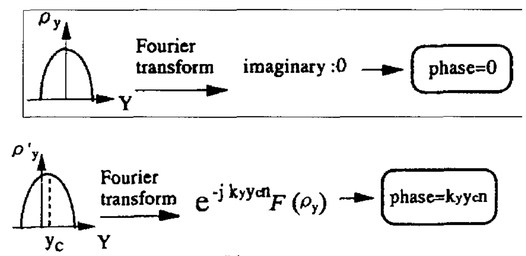

Fig. 3(b) Phase of the spectrum of the symmetric density distribution

Fig. 3 Explanation of the constraint conditions

where, y_c is a constant, which affects the reconstructed image as a position of symmetric axis of symmetric density distribution, but it does not cause any artifact in the image.

IV. SIMULATION RESULTS

The proposed method was evaluated by simulation experiments using a Shepp and Logan phantom shown in Fig. 4(a)[15 ~ 17]. The x and y directional motions were given by

$$\Delta_x(n) = 1.8\cos(16nk_x) + 1.8\sin(16nk_x) \tag{11}$$

$$\Delta_y(n) = 1.8\cos(16nk_y) + 1.8\sin(16nk_y) \tag{12}$$

$$(k_x = k_y = 2\pi / 256)$$

The reconstructed MR image with an artifact due to the above motion is shown in Fig. 4(b). First, the cancellation of the x directional motion component was done. The amplitude of the spectrum of the MRI signal without the x directional motion and with the x directional motion is shown in Fig. 4(c) and Fig. 4(d), respectively. The non-zero area of the amplitude is shown as a white area, and the zero area of the amplitude is shown as a black area. The edges between zero and non-zero in Fig. 4(c) show as a straight line, and the edges in Fig. 4(d) do not show as a straight line. The spectrum data in x direction is shifted to let the edge of the spectrum make a straight line. On the basis of this shifted spectrum data, the reconstructed MR image is shown in Fig. 4(e). The artifact was partly canceled.

The remaining motion component was y directional motion. It was canceled by the algorithm mentioned above. Fig. 4(f) shows the density function along a y directional line which passes through the edge of the phantom. Fig. 4(g) shows the phase of the spectrum along

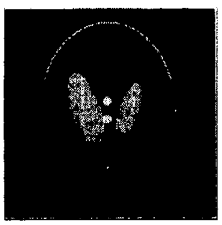

Fig. 4(a) Original image

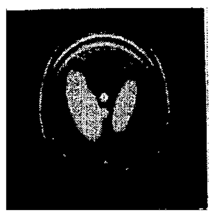

Fig. 4(b) MR image with artifact

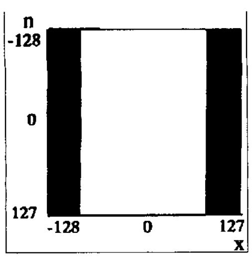

Fig. 4(c) Edge of amplitude of F_{xn}

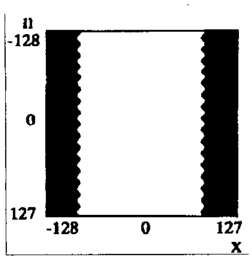

Fig. 4(d) Edge of amplitude of F'_{xn}

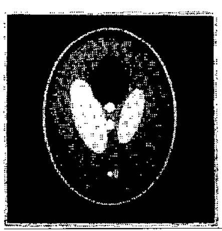

Fig. 4(e) Reconstructed image shifting F'_{xn}

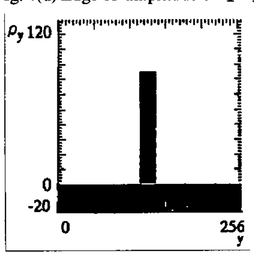

Fig. 4(f) Density distributionafter on a y directional line

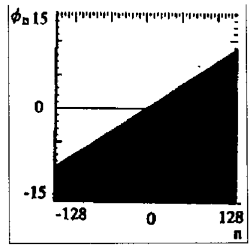

Fig. 4(g) Phase of F_{xn}, ϕ_{xn}

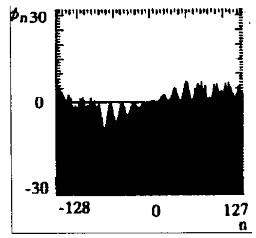

Fig. 4(h) Phase of F'_{xn}, ϕ'_{xn}

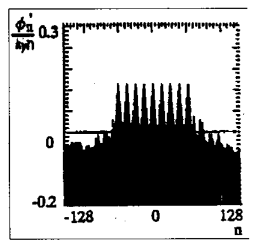

Fig. 4(i) Estimated y directional motion, ϕ'_{xn} / nk_y

Fig. 4(j) Reconstructional MRI after canceling the motion

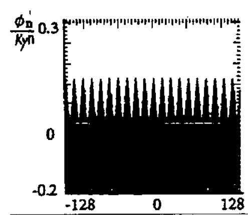

Fig. 4(k) ϕ'_{xn} / nk_y after lation processing

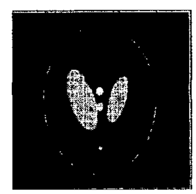

Fig. 4(l) Reconstructed MRI extrapo- after canceling the extrapolated motion

Fig. 4 Cancellation of the 2-D translational motion artifact

the y directional line without y directional motion, and the phase ϕ_{xn} is a linear function of n. Fig. 4(h) shows the phase ϕ'_{xn} when the y directional motion $\Delta_y(n)$ occured. Fig. 4(i) shows motion $\Delta_y(n)$ occured. Fig. 4(i) shows the ϕ'_{xn} / nk_y, which is regarded as the y directional motion.

With regard to the cancellation of the y directional motion, the phase of MRI ϕ'_{xn} is calculated by Eq. (7). In order to decide the m, the ϕ'_n of two adjacent points are assumed to be continuous, shown as follows:

$$\left|\phi'_n - \phi'_{n-1}\right| = \left|nk_y(\Delta_n - \Delta_{n-1}) + k_y\Delta_n + \phi_n - \phi_{n-1}\right| < \pi \qquad (13)$$

When the n is large and the change of motion between two adjacent points is not small, Eq. (13) is not to be satisfied and the estimation of motion may cause some error. However, the error in the large n area only causes high frequency artifacts as shown in Fig. 4(j). It affected the quality of MRI a little bit. Furthermore, if the change of motions is assumed to be smooth, the error of the estimation of ϕ_{xn}/nk_y can be corrected by extrapolation processing. The corrected ϕ'_{xn} is shown in Fig. 4(k), and the reconstructed MRI from the corrected ϕ'_{xn} is shown in Fig. 4(l). Furthermore, the constraint condition requites symmetric density distribution along a y directional line.

V. DISCUSSION

Several problems in the above algorithm are discussed in this section. With regard to the cancellation of the x directional motion, only an integer pixel unit motion is canceled, that is, the subpixel motion is neglected here. This is also a part of the reason that some artifacts remain in the final reconstructed MRI. However, the subpixel motion does not cause a large artifact in the reconstructed MRI. This is shown in the following simulation result. Fig. 5(a) is the reconstructed MR image when there is the subpixel motion in x direction as follows:

$$\Delta_x(n) = 0.3\cos(16nk_x) + 0.3\sin(16nk_x) \qquad (14)$$

Fig. 5(b) is the reconstructed MR image when there is the same subpixel motion as $\Delta_x(n)$ in the y direction.

$$\Delta_y(n) = 0.3\cos(16nk_y) + 0.3\sin(16nk_y) \qquad (15).$$

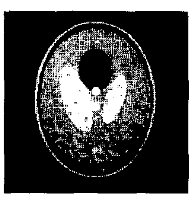

Fig. 5(a) MR image with artifact due to x directional subpixel motion

Fig. 5(b) MR image with artifact due to y directional subpixel motion

Fig. 5 Comparision of artifacts due to x and y directional motion

In the case of the comparision of artifacts due to subpixel motion as shown in Fig. 5(a) and Fig. 5(b), it can mean that the affection due to y directional motion is bigger than it due to x directional motion.

Fig. 6(a) Original image

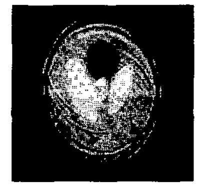

Fig. 6(b) MR image with artifact

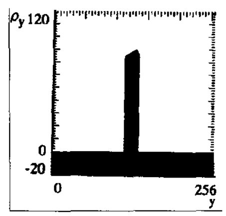

Fig. 6(c) Asymmetric density distribution on y directional line

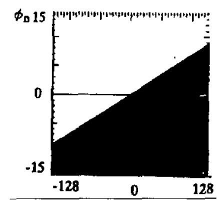

Fig. 6(d) Phase of x directional spectrum without motion

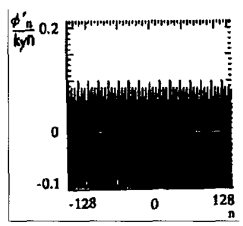

Fig. 6(e) Estimation of y directional motions, ϕ'_{xn}/nk_y

Fig. 6(f) Reconstructed image after canceling the motion artifact

Fig. 6 Simulation for Asymmetric Density Distribution

Fig. 6 shows the simulation result of which the density distribution along a y directional line through a subcutaneous fat area is not perfectly symmetrical and the motions are the same as Eq. (11)~(12). Fig. 6(a) shows the original MRI. Fig. 6(b) shows the MRI before canceling the artifact. Fig. 6(c) shows the asymmetric density distribution along a y directional line. Fig. 6(d) shows the phase of x directional spectrum without motion. Fig. 6(e) shows the estimation of y directional motions, i.e., ϕ'_{xn}/nk_y, after canceling x directional motions. Fig. 6(f) shows the reconstructed MRI after canceling the y directional motion component. The result shows the proposed method to be still effective in such a general case.

Acknowledgement: Thank you for the supports from Dr. George E. Hedrick, Computer Science Dept., Oklahoma State University.

VI. CONCLUSIONS

On the basis of principles of MRI, a new algorithm for canceling the MRI artifact due to 2-D translational motion in the image plane is described. Unlike the conventional iterative phase retrieval algorithm, in which there is no guarantee for the convergence, a direct method for estimating the motion is presented. In the case of previous approaches, the motions in the x(read out) direction and the y(phase encoding) direction were estimated simultaneously. However, the features of the x and y directional motions are different from each other. By analyzing their features, each x and y directional motion is canceled by different algorithms in two steps. First, it is noticed that the x directional motion corresponds to a shift of the x directional spectrum of the MRI signal, and the non-zero area of the spectrum just corresponds to the projected area of the density function on the x axis. So the motion is estimated by tracing the edges between the non-zero area and zero area of the spectrum, and the x directional motion is canceled by shifting the spectrum in a reverse direction. Next, the y directional motion is canceled by using a new constraint condition, with which the motion component and the true image component can be separated. The effectiveness of this algorithm was shown by using a phantom image with simulated motion. On the other hand, this algorithm was only applied to rigid motions, and it must be further studied to apply this algorithm to non-rigid motions. This algorithm was only tested with simulations until now, it must be tested with a real MRI experiment. Furthermore, the algorithm requires a symmetric density distribution along a y directional line. If such a line does not exist, an isotropic object is appended on the target prior to the imaging test.

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